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論文題目	Geothermal resource assessment in shallow crust of Japan by three-dimensional temperature modeling using satellite imagery and well-logging dataset （衛星画像と坑井検層データセットを用いた日本列島地殻表層の 3 次元温度分布モデリングと地熱資源評価）		

（論文内容の要旨）

This dissertation is the results of geothermal resource assessment in shallow crust of Japan by a new method that combines three-dimensional temperature modeling using well-logging dataset and land-surface temperature (LST) mapping using thermal infrared remote sensing (TIR) imagery. It is composed of seven chapters.

Chapter 1 introduces this PhD research by describing the background and motivations. Geothermal energy, one of renewable energy, plays an important role in reducing carbon-dioxide emission and ensuring self-sufficiency of energy supply because of its huge amount of resource. Another merit is stable energy supply regardless weather conditions as compared to solar and wind power generation. For enhancement of the use and development of geothermal resource, accurate assessment of geothermal system including geological structure, fluid flow, and subsurface temperature (SST) from the near surface down to great depths is indispensable. In addition, detailed mapping LST is effective to detect geothermal manifestations on the ground from extensive areas. Based on these backgrounds, this research is aimed to develop the methods for estimating SST and LST, characterize the temperature distributions, and integrate SST and LST for geothermal resource assessment.

Chapter 2 describes the details of main methods used for estimating SST and LST including remote sensing, geographic information systems (GIS), geostatistics, and their related R packages. Among many algorithm of LST retrieval using TIR, a method using only one parameter (emissivity of surface material) was clarified to be the most suitable because this research used many low cloud-cover scenes with different seasons. At first, temperature at top of atmosphere is calculated using the Planck’s law and then, it is corrected by considering the land surface emissivity. As for SST, kriging with external drift (KED) is the best because the temperature data are not statistically stationary and increase with depth, which expressed as a trend. For simplification, a global linear trend related to the physics of conduction was adopted for the log-transformed temperature data used for 3D KED estimation.

Chapter 3 summarizes the prototype of data and its integration by remote sensing, GIS, and geostatistics. For this integration, a coordinate reference system of Japan was developed. Next, details of all dataset used in this research, which are well-logging temperature data, TIR data from Landsat 8 and MODIS, and geothermal manifestation data such as location of active volcanoes, and land-use land-cover map (LULC) based on a classification of ALOS images are described.

Chapter 4 proposed a method to identify two thermal types of heat transfer, conduction and convection, in the crust from the temperature-logging dataset. This identification is essential to geothermal exploration and reservoir mapping because it is related to geothermal fluids and convective zones have preferable energy potential with higher temperatures in shallow depths. This identification was accomplished by a statistical-based

method and coefficient of determination of 0.9 was revealed to be a proper threshold to discriminate the two types.

Chapter 5 describes an application of the proposed methods to Hokkaido island and the results. A set of the 28,476 well-logging temperature datapoints collected from 433 sites and 13 Landsat 8 TIRS images were used to clarify the extensive variability of temperatures in the upper crust and on the surface over Hokkaido in northern Japan. The SST model was constructed using the dataset and a geostatistical method, KED while the LST map was first produced using the universal algorithm examined in Chapter 2, and then transformed into the residual form by subtracting the scene average temperature to detect local thermal anomalies. 3D SST was calculated for depths of 100 m to 1500 m and a unit grid size of 1000 m by 1000 m and 100 m in the horizontal and vertical directions, respectively. Remarkable features were detected from the SST model by KED; specifically, high temperature zones were mostly located in the western region and a part of the eastern region in accordance with the distribution of Quaternary volcanoes and high heat flow, while the central region was dominated by low temperatures due to the thick cover of sedimentary rocks. Although LST is mostly controlled by LULC, such as urban areas and topography, high temperature anomaly zones were detected in the high SST areas. These findings demonstrate the effectiveness of the combination of subsurface and surface temperatures using geostatistical spatial modeling and TIR remote sensing for identification of zones with high potential for geothermal resources.

Chapter 6 extends the analysis of Chapter 5 to whole Japan island using the 85,545 well-logging temperature datapoints collected from 1,125 sites. From the result of SST, the high temperature zones are appeared in eastern Hokkaido, northeast Honshu, middle of Honshu, and southern Kyushu. In particular, northeast Honshu region is characterized by the most concentration of the high temperature zones. These distributions are concordant with the locations of active and Quaternary volcanoes. There are high temperature zones unrelated to the volcanoes such as the southern end of Kii peninsula. Latent magma can be estimated under this peninsula associate with the subduction of the Philippine Sea Plate. Using the SST, heat energy was calculated over Japan, which implies high recourse potential in the northern and southern Tohoku and middle Honshu regions. LST obtained by the set of MODIS scenery also reveals the high potentials of these regions.

Chapter 7 summarizes the main results of each chapter, contribution of the results to geothermal science and technology, and future significant works.

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（論文審査の結果の要旨）

地熱発電には少ない二酸化炭素排出量,相対的に高い出力と設備稼働率などの利点があり，世界的に需要が増加している。この発電には蒸気・熱水を含む高温の貯留層の存在が不可欠なので,地殻浅部の広域的な温度分布は地熱資源賦存の評価において重要となる。しかしながら，地表と地下を含む地温の広域的な 3 次元分布を推定するための手法は確立されておらず，地温構造の詳細は明らかになっていない。この問題に対し，本論文は地球統計学とリモートセンシングの 2 つの手法を組み合わせることを試み,地温の空間的相関構造と温度変化の物理則を考慮することで日本列島の地殻浅部の地温構造を推定できたとともに，これと地表温度とを関連付けられた初めての研究である。以下に得られた成果の概要をまとめる。

1. 空間分解能が高い Landsat 8 衛星の熱赤外バンド画像の放射輝度データから地表温度を算定するのに最も適した手法を特定し，地表物質の放射率を適切に設定すれば 2 °C 以内の算定誤差であることを示した。また，各シーンでの平均温度を差し引いた後に多くのシーンをモザイク処理することで，広域から地表温度異常地点の検出を可能にした。
2. 坑井を利用した温度検層データの深度方向の変化パターンに注目し，これを熱伝導型と対流型に分類するための統計学的手法を提案した。この適用によって，対流型の坑井の位置は活火山の近傍 50 km 以内に限られることがわかった。
3. 地温データの空間的相関構造は，相関距離が大きく異なる 2 つのモデルの和で近似できることを見出した。また，深度方向の温度変化を伝導型，対流型ごとに多項式で近似し，これをトレンド成分としたクリギングによれば地温の 3 次元分布を高精度で推定できることを示した。
4. 日本列島全体における 1,125 地点での計 85,545 個の温度検層データを用い，1 km×1 km×0.1 km のボクセルサイズと 3 .によるトレンド付きクリギングの適用によって，深度 1 km までの地温の 3 次元分布を明らかにした。これによる高温域は活火山周辺や断層密集域などに位置し，地殻熱流量の大きな地区，および 1 . の熱赤外リモートセンシング法による地表の局所的高温域に対応した。さらに，地表温度と地温から熱量を算出し，日本列島において地熱資源のポテンシャルが高い地区を特定できるようになった。

以上，本論文は，熱赤外衛星画像データと 3 次元地温モデリングの有用性を実証したものであり，世界的な地熱資源評価への展開，および火山学，地殻変動学などの他分野との連携も期待でき，学術上，実際上寄与するところが少なくない。よって，本論文は博士（工学）の学位論文として価値あるものと認める。また，平成 27 年 2 月 23 日，論文内容とそれに関連した事項について試問を行い,申請者が博士後期課程学位取得基準を満たしていることを確認し，合格と認めた。